TECHNICAL MEMORANDUM

To: **Kim Tower, Environmental Technician**
Department of Marine and Environmental Affairs

From: **Brian Howes, Ph.D., Director, Coastal Systems Program (SMAST-UMD)**
Roland Samimy Ph.D., Sr. Research Associate, Coastal Systems Program
David Schlezinger, Ph.D., Sr. Research Manager, Coastal Systems Program
Michael Bartlett, Technical Associate, Coastal Systems Program

Re: **Hydrodynamic Data Collection in Partial Fulfillment of the Massachusetts Estuaries Project Linked Watershed-Embayment Nitrogen Management Approach for the Plymouth-Duxbury Harbor-Kingston Bay Embayment System**

Date: **June 26, 2013**

This technical memorandum summarizes the hydrodynamic field data collection efforts to support future hydrodynamic modeling of the Plymouth Harbor, Duxbury Harbor and the Kingston Bay estuary system (Figure 1a, 1b, 1c, 1d). For this system and in the future as funding becomes available, a final calibrated hydrodynamic model will be developed under the umbrella of the Massachusetts Estuaries Project (MEP). This modeling is needed to implement the MEP's Linked Watershed-Embayment Modeling Approach, central to evaluating water and habitat quality of this complex estuary, as well as a tool for determination of nitrogen loading "thresholds".

The hydrodynamic field data collection undertaken under this contract for scientific services is the basis for the MEP hydrodynamic model which generates tidal flushing information that is utilized as the basis for a quantitative evaluation of water quality. During completion of the MEP analysis of the system, nutrient loading data previously developed for the Town of Plymouth under separate contracts with the SMAST-Coastal Systems Program will be combined with measured environmental parameters within the overall embayment system to become the basis for an advanced water quality model based on total nitrogen concentrations. These linked models provide the Town of

Plymouth with a tool for evaluating estuarine response to both watershed and in-estuary management alternatives.

Figure 1a - Plymouth Harbor, Kingston Harbor and Duxbury Bay Embayment System with locations of Temperature-Depth-Recorders (triangles marked PLY#) as well as Acoustic Doppler Current Profiler (TR1 and TR2) transects.

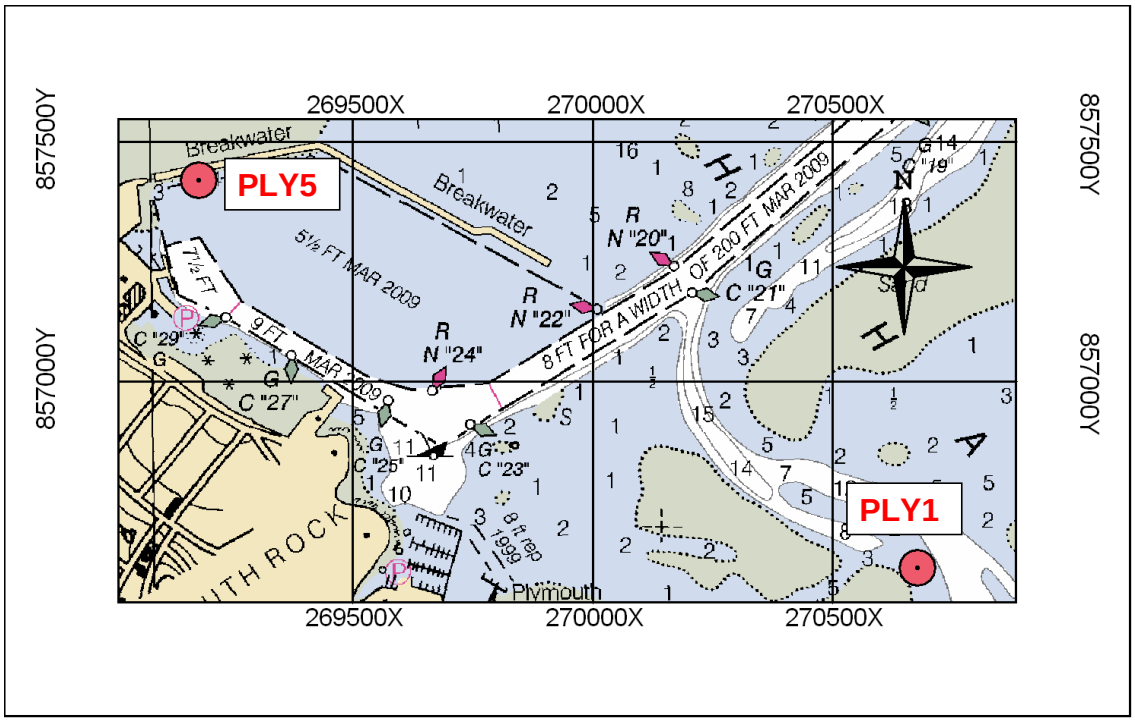

Figure 1b – Detail of location of sites of Temperature-Depth-Recorders (TDR) deployments: Town of Plymouth boat basin (PLY5) and Plymouth Harbor (PLY1).

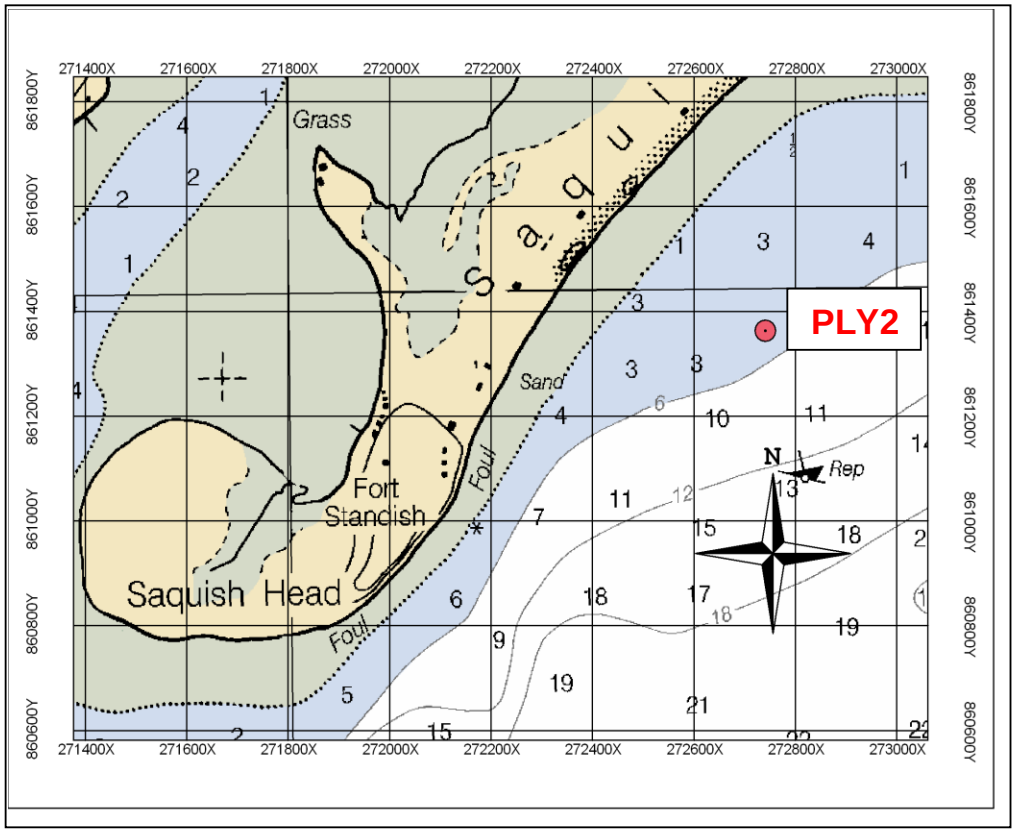

Figure 1c – Detail of location of Temperature-Depth-Recorder (TDR) deployed offshore relative to the embayment inlet (PLY2).

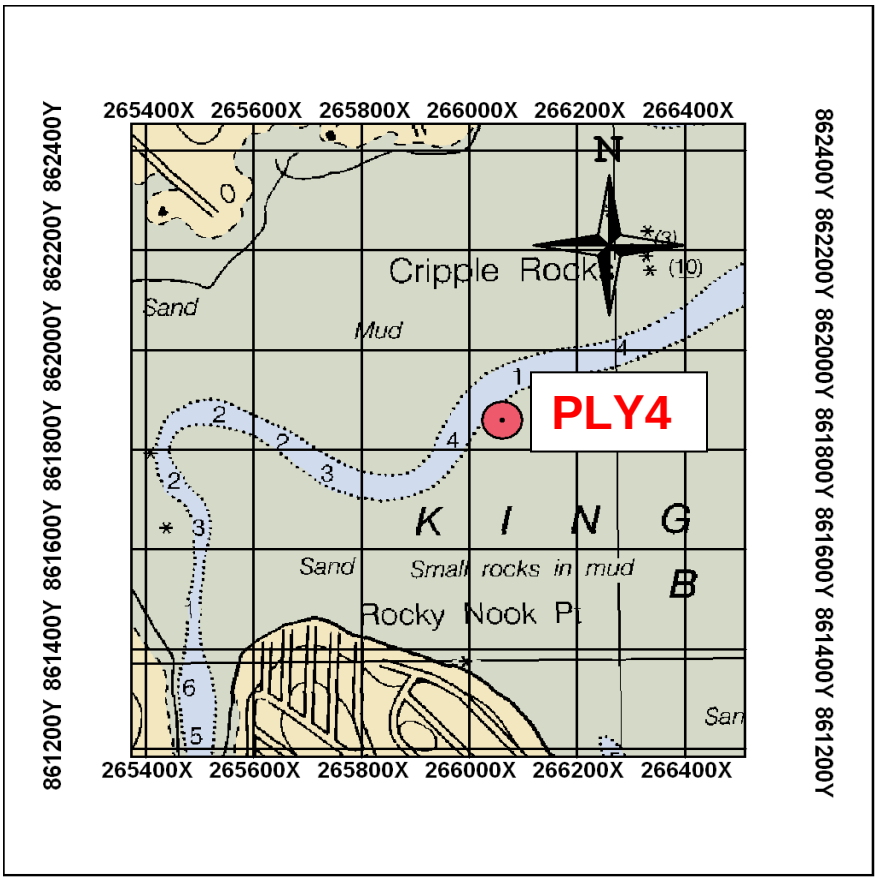

Figure 1d. Detail of location of Temperature-Depth-Recorder (TDR) deployed northeast of the entrance to the Jones River in Kingston Bay (PLY4).

In general, water quality studies of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents and circulation, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

Estuarine water quality is dependent upon nutrient and pollutant loading and the processes that help flush nutrients and pollutants from the estuary (e.g., tides and biological processes). Relatively low nutrient and pollutant loading and efficient tidal flushing typically result in high water quality. The ability of an estuary to flush nutrients

and pollutants is proportional to the volume of water exchanged with a high quality water body (i.e. Cape Cod Bay, Buzzards Bay, Vineyard Sound, Atlantic Ocean). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Plymouth-Kingston and Duxbury embayment system, the most important parameters are the tide range along with the basin morphology (shape, length and depth) of the estuary, thus the need for detailed survey of embayment bathymetry as well as tidal stage throughout the system. Current velocity data collected at strategic locations in the estuary also serve to confirm the accuracy of the future numerical model, once developed, to quantify flushing of the overall system, which is needed to construct the nitrogen based water quality model.

FIELD DATA COLLECTION AND ANALYSIS

Detailed field measurements of bathymetry and tide stage, coupled to current measurements were undertaken by SMAST scientists for the Town of Plymouth for this project. These data provide:

- Accurate definition of the geometry and boundary conditions of the tidal areas of this large estuarine complex for use in the numerical model

- Actual field measurements of hydrodynamic behavior to calibrate and verify the hydrodynamic model results.

System geometry is defined by the shoreline of the system, including all coves, creeks, and marshes, as well as accompanying depth (or bathymetric) information. The three-dimensional surface of the estuary is mapped as accurately as possible, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills and shoals, marsh elevations, and inter-tidal flats. Hence, the MEP approach includes an effort to collect bathymetric information by field surveys, as described below.

Boundary conditions for the numerical model consist of variations of water surface elevations measured in the embayment being evaluated. These variations result principally from tides, and provide the dominant hydraulic forcing for the system, and are the principal forcing function applied to the model. Five pressure sensors were installed throughout the embayment system at selected interior and exterior locations to measure variations of water surface elevation along the length of the system (gage locations are shown in Figure 1a, 1b, 1c, 1d). These measurements will be used by the MEP to identify potential restrictions to tidal flow and to calibrate and verify the hydrodynamic model results and to assure that the dynamics of the physical system were properly simulated.

Bathymetry

Bathymetry data collection (depth measurement) was conducted on six hydrographic surveys. For areas where data collection was limited, NOAA LIDAR survey data was used to complement the SMAST field surveys (12th, 19th, 29th of November and the 3rd and 4th of December 2012). Due to the size and unique

characteristics of the Plymouth Harbor system, longitudinal survey transects were spaced at 400 meter intervals to provide high resolution coverage. Within Plymouth Harbor proper, survey line spacing was decreased to 150 meter intervals to increase spatial coverage. Particular attention was focused on the numerous channels (150 meter transect spacing interval) that intersect the system in order to capture the variability in the bottom bathymetry within these critical areas.

The bathymetry surveying was conducted over a three month period from early October 2012 to early January 2013. Survey transects were concentrated in the vicinity of the inlet to the system as well as throughout the channel network were the greatest variability in bottom bathymetry was expected. Survey transects were run along the channel perimeter, the channel midline, and the channel width. Survey transects along the channel width were spaced at periodic intervals throughout the channel area to capture the cross sectional variation in the bottom bathymetry. Using a single beam precision fathometer (Odom Hydrotrac, 0.01 meter resolution) depth measurements were collected by shallow draft vessel. Global position data (Latitude, Longitude) was also collected using a differential GPS (Leica) with an accuracy 0.05 – 1.0 meters. All depth and position data were recorded into a laptop computer using hydrographic software (HYPACK) integrating the DGPS position and depth measurement into a single data set. Integrating the data in this manner enables the depth measurement to be linked with a precise known position.

The raw measured water depths were corrected for tidal stage (from TDRs) to yield basin depths throughout the estuary to be referenced to the North American Vertical Datum of 1988 (NAVD88) vertical datum. Reference to a single datum provides a correction of the bathymetric data for changing water levels due to the tide changes during the lengthy surveys. Once rectified, the finished, processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts Mainland State Plane 1983 coordinates) and vertical elevation of the bottom (z). In the future, as the MEP hydrodynamic modeling task is undertaken for the Town of Plymouth, these xyz files will be interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure 2.

Based on the detailed bathymetry survey of the entire embayment system, it is evident that bottom elevations throughout the Plymouth-Kingston-Duxbury embayment system are well below the NAVD88 elevation datum and therefore always submerged. In contrast, significant areas of the outer harbor east/northeast and south (west of Eel River) of the town boat basin experience periods of exposure during the low tide portion of the tidal cycle which will have to be properly accounted for through a wetting/drying function in the future hydrodynamic circulation model for the system.

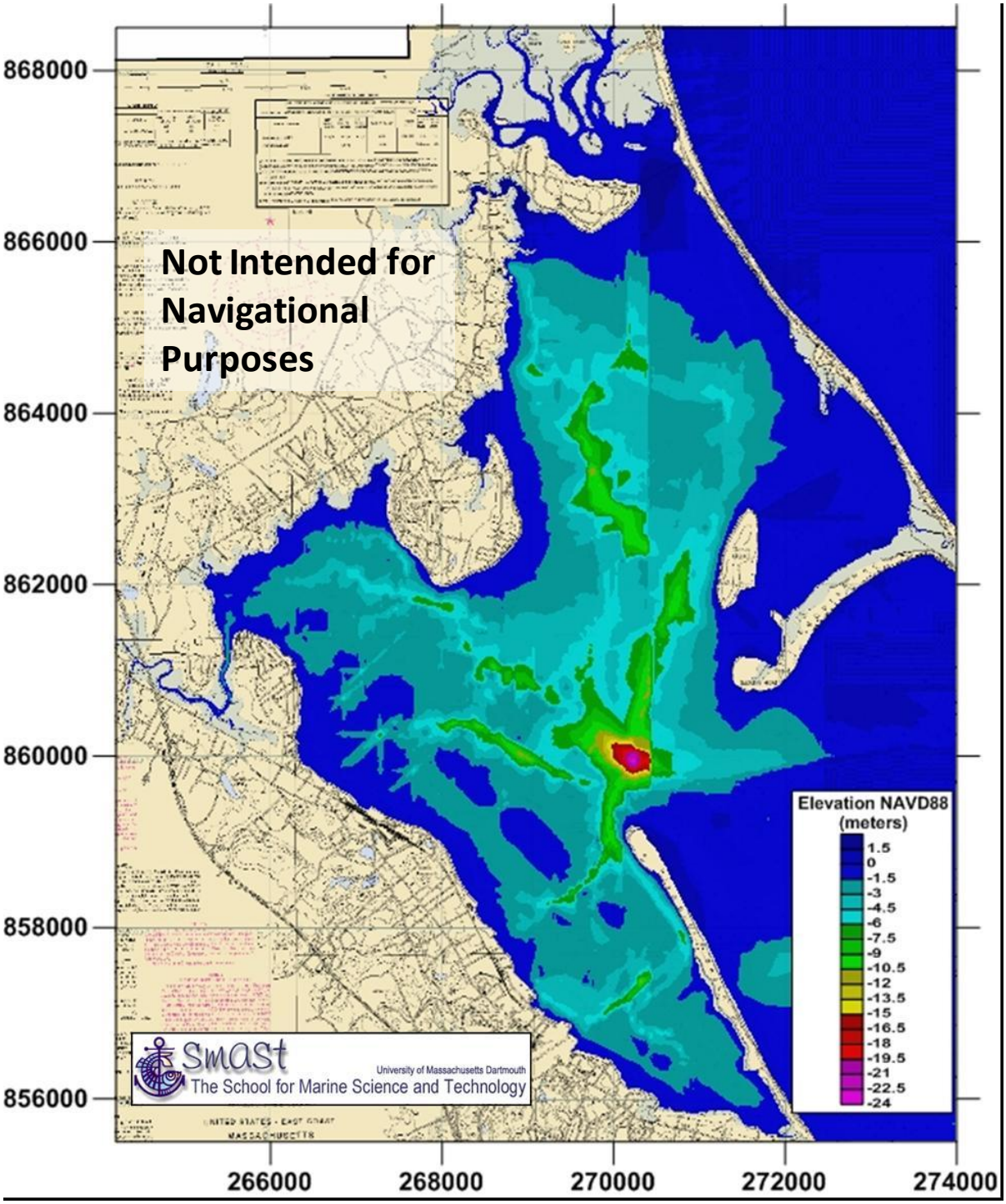

Figure 2 Bathymetric map of the Plymouth Harbor, Duxbury Harbor and Kingston Bay Embayment System. Bathymetric elevations are relative to the North American Vertical Datum of 1988 (NAVD88) vertical datum in feet. NOT INTENDED FOR NAVIGATIONAL PURPOSES.

Not surprisingly, the largest depths measured and the quickest variation in depth occurred within the channels that intersect the harbor system with the sections of greater depth located in the areas encompassing Duxbury light, Plymouth Harbor Channel proper, Cowyard channel and the town boat basin (Figure 2). As such, the channels were surveyed in much greater detail than the tidal flats that exhibit very little change over large distances and areas.

Tide Data Collection and Analysis

The hydrodynamic properties of an estuarine system are affected by the physical characteristics of the system. Channel structure, marsh elevation, and tidal flats are characteristics of the system structure that define and influence the hydrodynamic behavior of a particular system as well as the temporal and spatial tidal changes occurring across the system. To properly understand these characteristics and their effect on the hydrodynamic modeling, detailed hydrodynamic data collection is required. Variations in water surface elevation were measured using Temperature-Depth Recorders (TDR) deployed at four (4) locations within (internal) the Plymouth-Kingston-Duxbury embayment system and at one (1) offshore location just outside of the main inlet (external) to the overall system. Two TDRs (PLY2a and PLY2b) were deployed at the offshore location to ensure 100 percent data recovery.

The Plymouth Harbor system is comprised of Plymouth Harbor, Kingston Bay, and Duxbury Bay/ Back River estuarine systems. For this complex system an intensive field bathymetric data collection effort (described above) was undertaken as well as tidal elevation data at multiple locations throughout the harbor system. In addition to the aforementioned hydrodynamic components, a tidal exchange survey was also conducted to collect data necessary to determine the hydrodynamic forces controlling the Plymouth Harbor system.

In order to measure the variations in water surface elevation associated with the tidal components, the temperature/depth recorders (TDRs) were deployed as follows:

Inshore TDR Locations

Plymouth Harbor (PLY1),
Town of Plymouth Boat Basin (PLY5),
Kingston Bay (PLY4),
Duxbury Bay/Back River (PLY3) - Instrument Failed

Offshore TDR Location

Offshore Northeast of Saquish Head inlet (PLY2a and 2b)

Specific locations (Lat/Lon) for each of the TDRs deployed are presented in Table 1. The tide data recorders were deployed and recovered via scuba diver. At each deployment site, water surface elevations were measured using a RTK GPS (Real time Kinetic GPS, Leica). This GPS system uses a base station network to provide real time

elevation data relative to NAVD88 datum (accuracy +/- 0.01m). Duration of deployment spanned 96 days beginning on October 8, 2012 and extending to January 14, 2013. The TDR deployment duration window provided the necessary time for the collection of the bathymetry data as well as completion of ADCP surveys for the analysis of ebb/flood current velocities. The tide records from the 6 TDRs were corrected for atmospheric pressure variations from nearest weather station (Plymouth Municipal Airport). Once corrected for atmospheric pressure, the data sets were converted to elevations relative to NAVD88 datum (Figures 3-12).

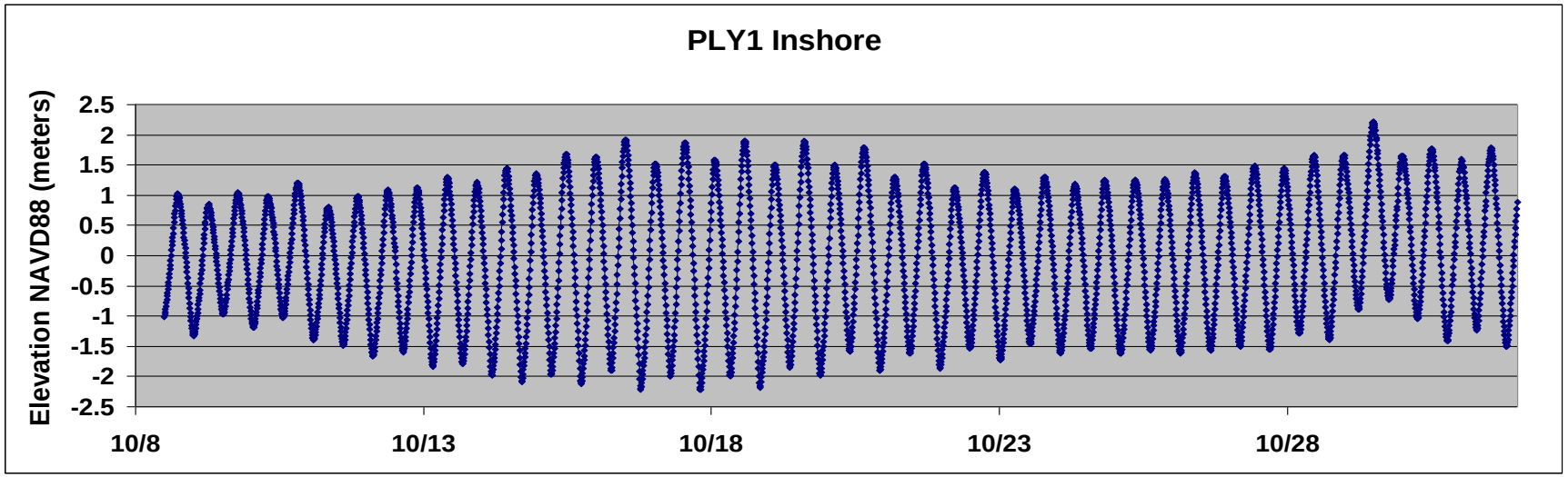

Figure 3. Water surface elevation data (October 2012) for Plymouth Harbor (PLY1) tide data recorder deployed within the Plymouth Harbor system. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

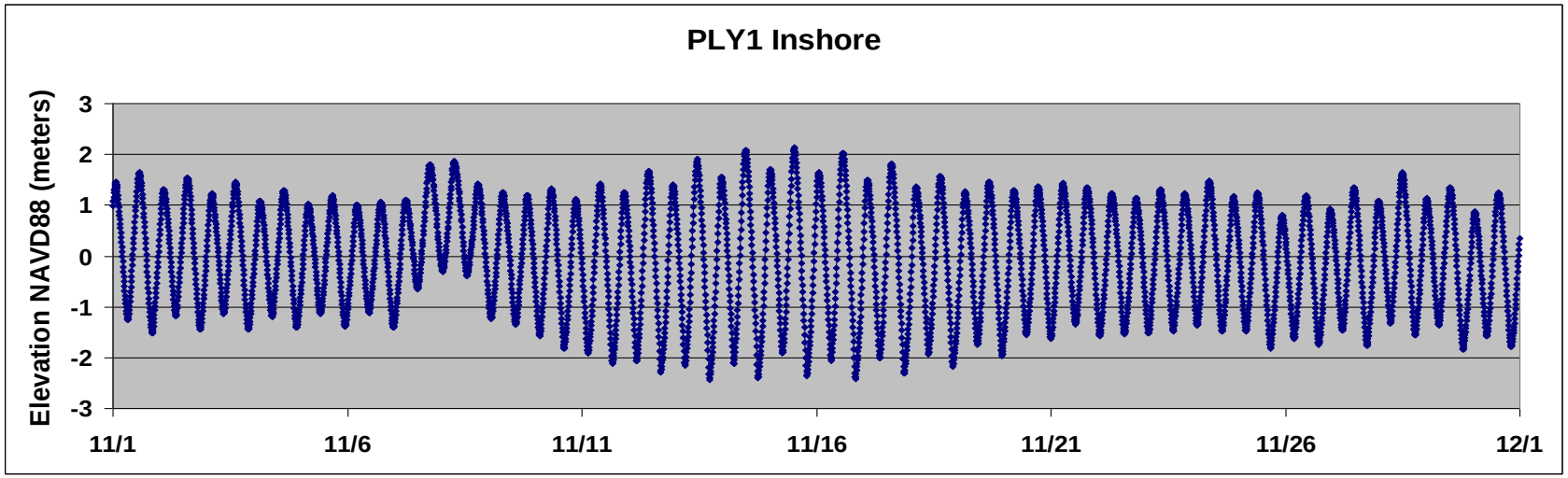

Figure 4. Water surface elevation data (November 2012) for Plymouth Harbor (PLY1) tide data recorder deployed within the Plymouth Harbor system. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

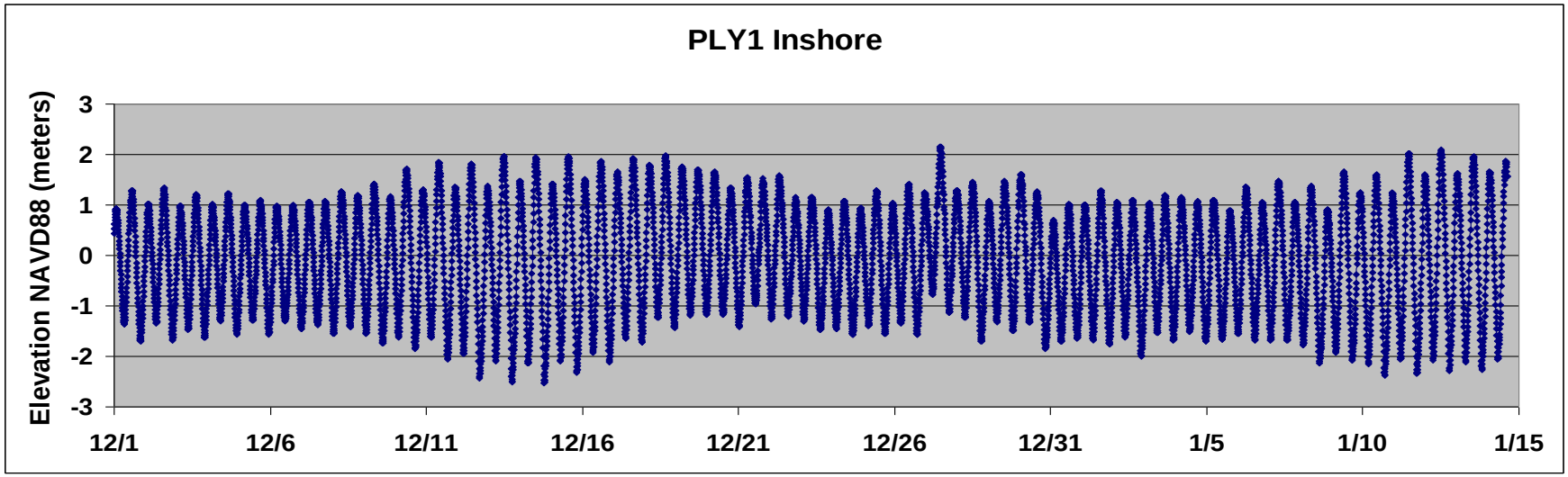

Figure 5. Water surface elevation data (December 2012 into January 2013) for Plymouth Harbor (PLY1) tide data recorder deployed within the Plymouth Harbor system. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

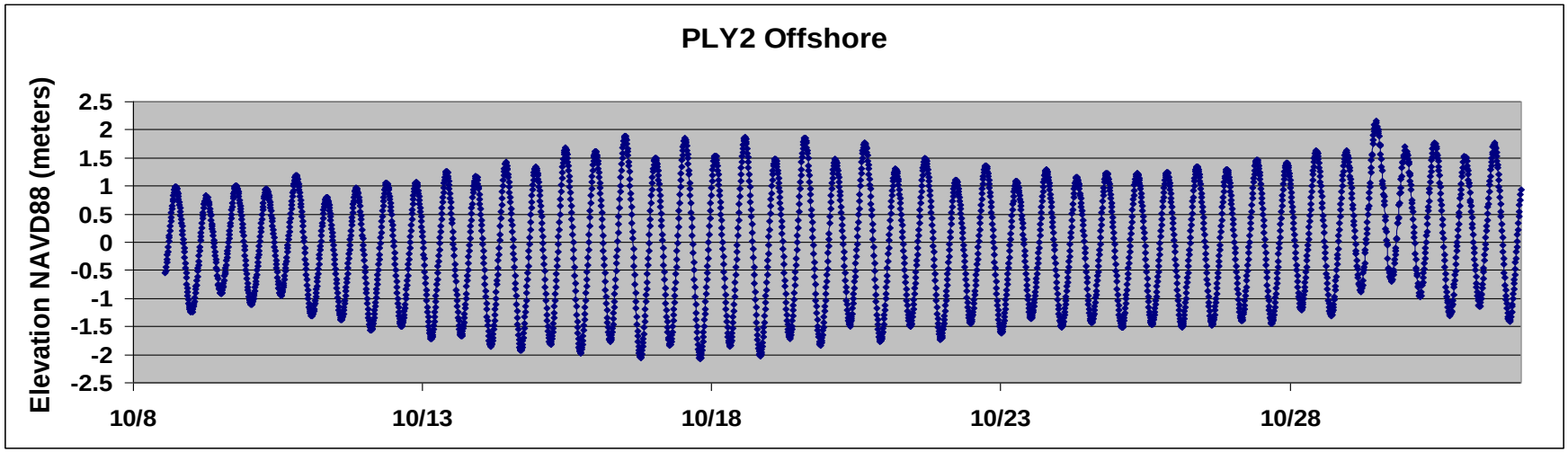

Figure 6. Monthly (October 2012) water surface elevation data for the Offshore Temperature-Depth Recorder (TDR) PLY2 deployed outside of the inlet in Cape Cod Bay. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

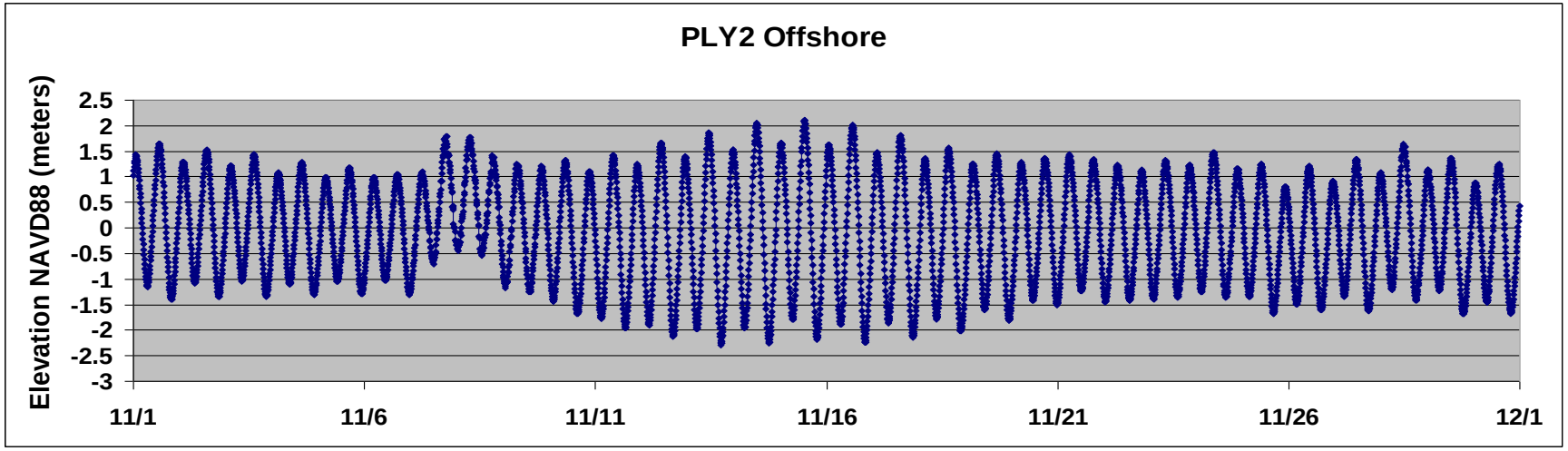

Figure 7. Monthly (November 2012) water surface elevation data for the Offshore Temperature-Depth Recorder (TDR) PLY2 deployed outside of the inlet in Cape Cod Bay. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

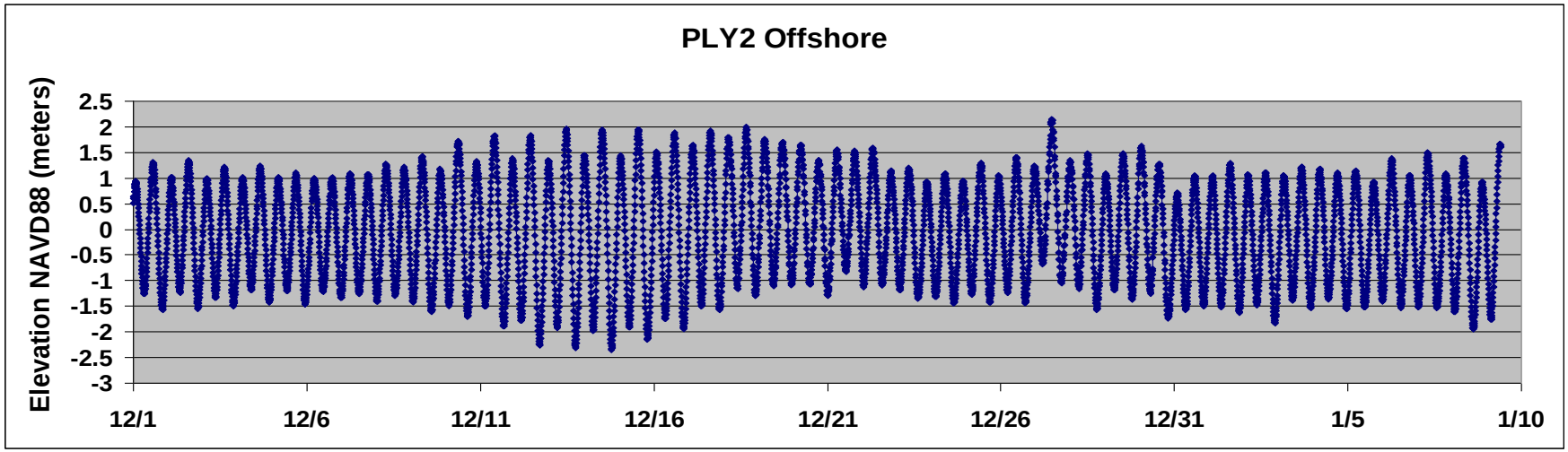

Figure 8. Monthly (December 2012 into January 2013) water surface elevation data for the Offshore Temperature-Depth Recorder (TDR) PLY2 deployed outside of the inlet in Cape Cod Bay. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

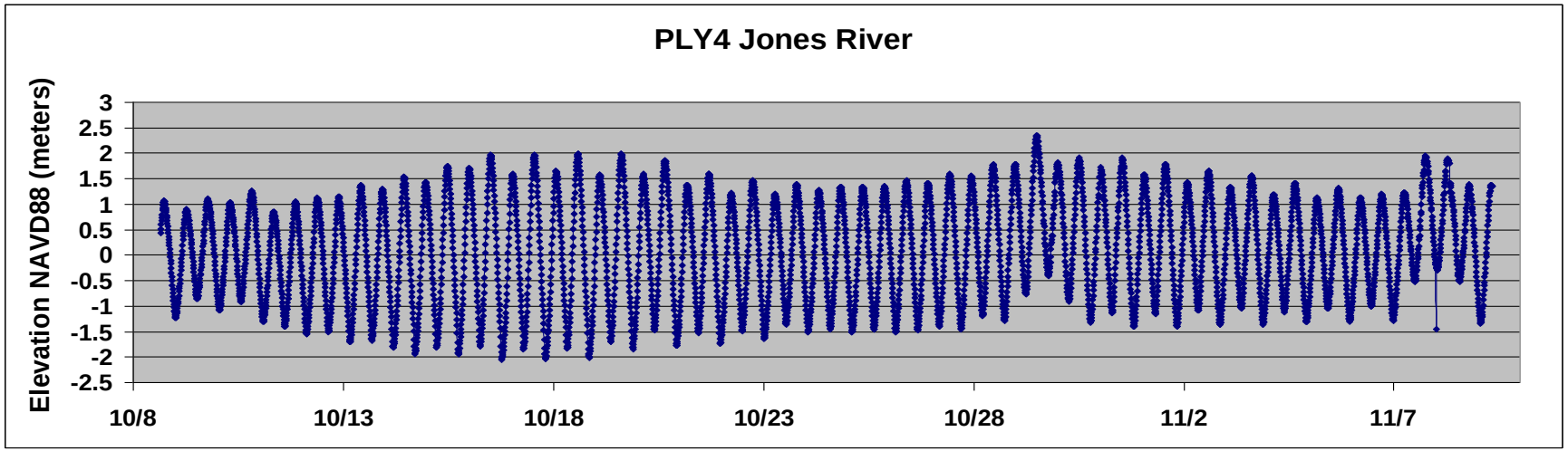

Figure 9. One month (October 2012) water surface elevation data for Temperature-Depth Recorder (TDR) PLY4 deployed near the mouth of the Jones River. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 30 day deployment period. Instrument failed after 30 days of deployment.

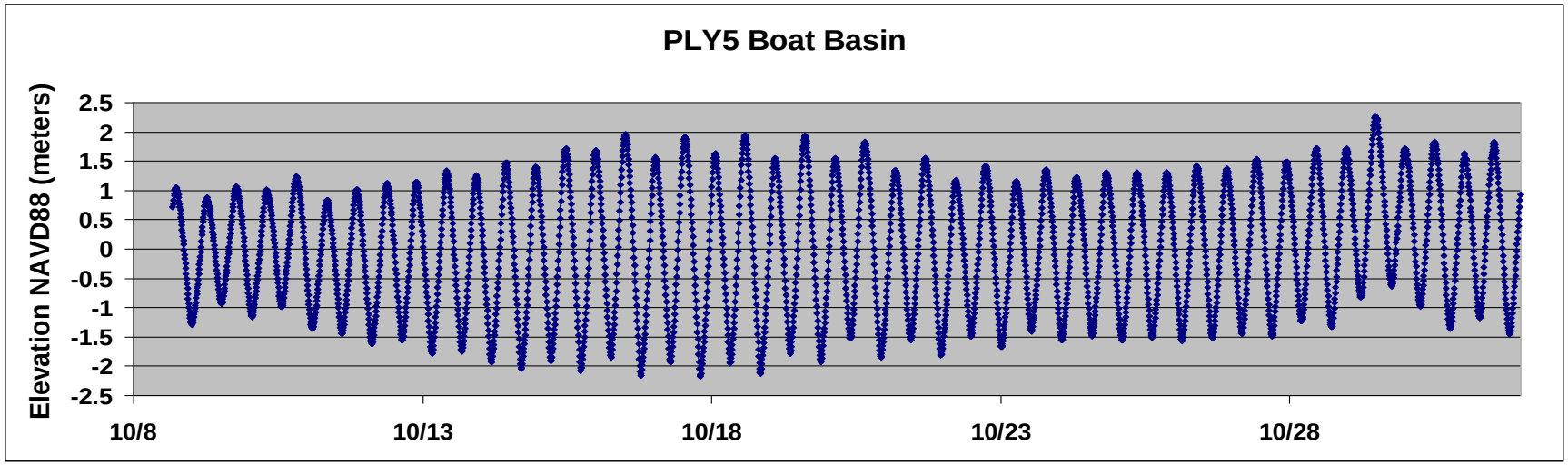

Figure 10. Monthly (October 2012) water surface elevation data for the Temperature-Depth Recorder (TDR) PLY5 deployed within the Town of Plymouth boat basin inside the breakwater in Plymouth Harbor proper. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

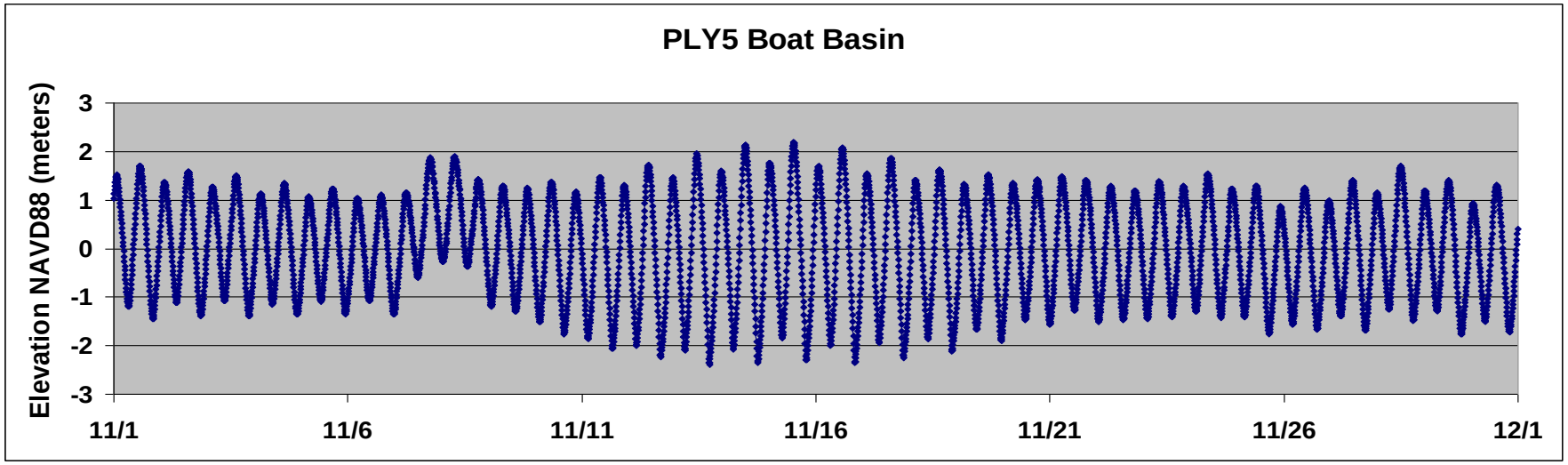

Figure 11. Monthly (November 2012) water surface elevation data for the Temperature-Depth Recorder (TDR) PLY5 deployed within the Town of Plymouth boat basin inside the breakwater in Plymouth Harbor proper. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

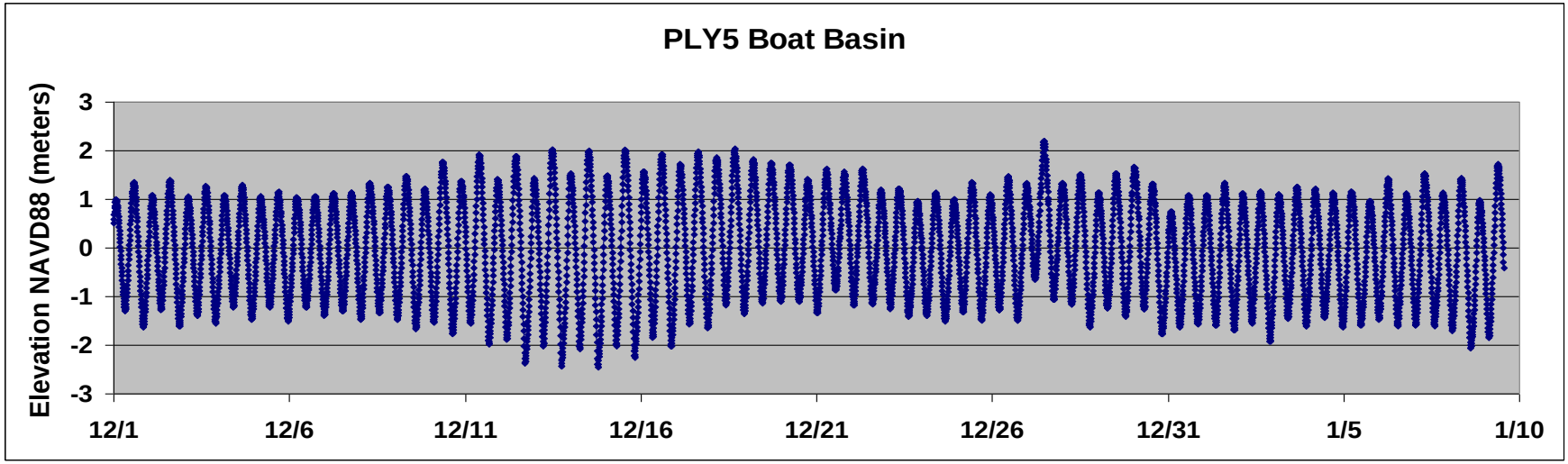

Figure 12. Monthly (December 2012 into January 2013) water surface elevation data for the Temperature-Depth Recorder (TDR) PLY5 deployed within the Town of Plymouth boat basin inside the breakwater in Plymouth Harbor proper. Tide elevations are referenced to NAVD88 (North American Vertical Datum 1988) for the 96 day deployment period.

			Elevation NAVD88		
			Min	Max	Mean
TDR	Lat	Lon	(meters)	(meters)	(meters)
PLY1	41.95667	70.64749	-2.529	2.211	-0.075
PLY2	41.99927	70.62199	-2.342	2.165	-0.048
PLY4	42.00433	70.70253	-2.044	2.352	0.107
PLY5	41.96409	70.66545	-2.460	2.266	-0.012

Table 1. Minimum, maximum and mean water surface elevations (NAVD88) for the four tide recorders during the 96 day deployment period (8-Oct-12 to 10-Jan-13).

When the tidal stages from all four TDR deployments (Figure 13) are referenced to a common datum, it is clear that there is little temporal lag between the recorded high tide at the offshore gage compared to the recorded high tide at more inshore locations within the system (e.g. Town of Plymouth boat basin (PLY5) or the mouth of the Jones River (PLY4)). Equally important, there is negligible damping of tidal heights, hence water exchange appears to be unrestricted between the offshore gauge and each inshore gauge site.

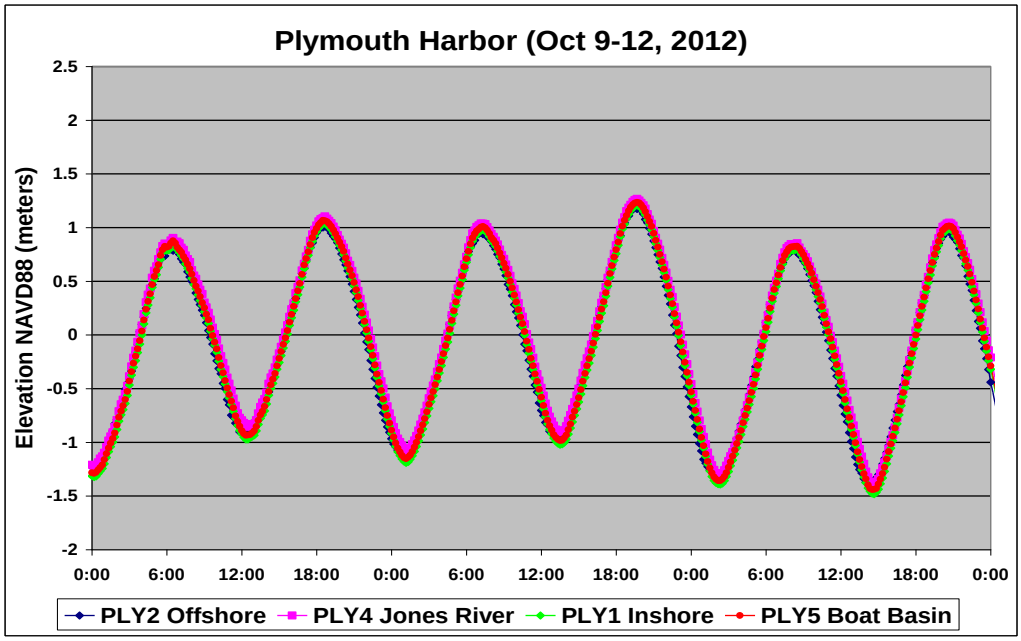

Figure 13. Plot showing the ~ three day water surface elevation data for the four tide recorders deployed in the Plymouth Harbor system.

The relatively long time-series of tide elevations captured several complete lunar cycles, creating a robust baseline for this estuary. This data will be integrated into future

hydrodynamic modeling undertaken through the MEP to calculate the tidal exchange volumes necessary for determining the flushing and nutrient characteristics of the embayment system.

ADCP Data Collection and Analysis

Cross-channel current measurements were surveyed at hourly intervals through a complete tidal cycle at two transect locations close to the inlet to the Plymouth-Kingston-Duxbury embayment system (Figure 14). Current measurements used were completed using an acoustic doppler current profiler (ADCP), which yields water velocities over the complete water column. By conducting cross-channel transects the total volume of water passing through the cross-section can be determined. This total volume is also an output of the hydrodynamic model, providing a straight forward comparison between modeled and observed volumes. The ADCP survey as undertaken in early November 2012 (Figure 16-21).

The ADCP survey was conducted at two locations chosen to optimize the velocity measurements of water exiting and entering the embayment system on the both the ebb and flood tides. The first survey transect (TR1) was located south of Duxbury Harbor extending from the eastern edge of the Cowyard channel to the western shore of Saquish Head (Figure 14). The second transect was located at the entrance to Plymouth Harbor Channel extending across the main channel east toward Plymouth Beach Point (Figure 14). Each survey transect location was established based on the system characteristics in order maximize velocity/discharge data collection during tidal flushing and maximize the value of the data collected for its use by the MEP in the future hydrodynamic modeling.

The tidal exchange survey occurred on the 1st of November 2012 and tidal stage was recorded simultaneously in order to relate measured cross sectional velocities to tidal height (Figure 15). Throughout the tide cycle, hourly cross channel (perpendicular to transect) velocity and discharge measurements were collected using a vessel mounted ADCP (Acoustic Doppler Current Profiler, (RDI-Teledyne Sentinel) integrated with a differential GPS unit (Leica, accuracy 0.5-1.0 meter). By integrating the DGPS and ADCP into a single data stream, the velocity/discharge data collected have a precise global position associated with a known velocity/discharge measurement at a specific time. The time is then related back to the associated TDR to determine the precise point in the tide stage, since velocity varies throughout the tidal cycle.

From the field surveys completed, it appears that there is tidal symmetry along both survey transects with opposite phases of the tide cycle dominating each survey area. The northern survey area (TR1) experiences a flood tide which flows in the northern direction with the ebb tide flowing to the south. However, the southern survey area the opposite occurs during a tidal cycle with a flood tide flowing to the south and the ebb tide to the north. This tidal characteristic for each survey transect can be seen in Figures 22 and 23 below.

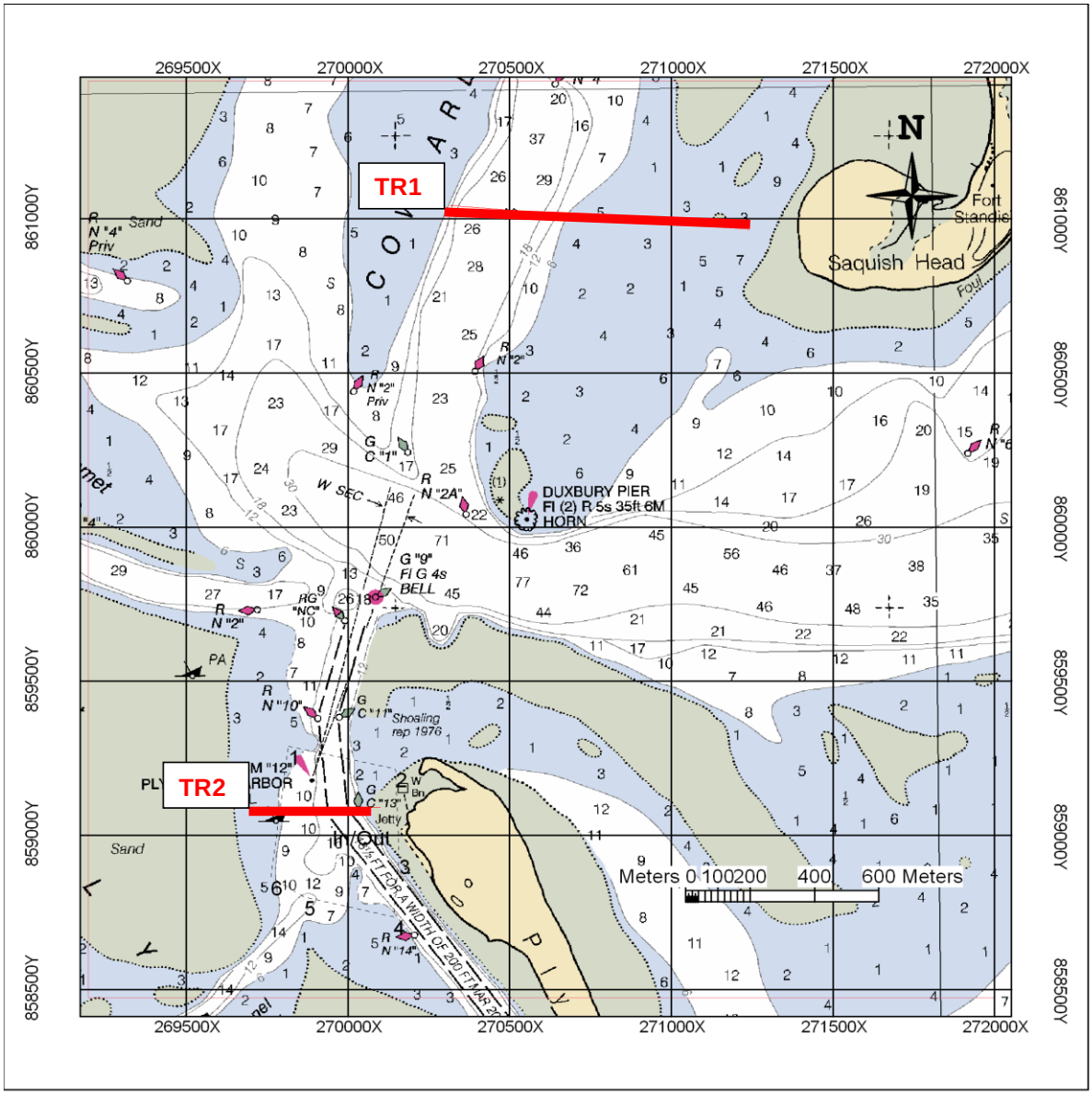

Figure 14. ADCP survey map depicting the two transect lines (TR1 and TR2) surveyed for velocity and discharge measurements over a complete tidal cycle (ebb and flood).

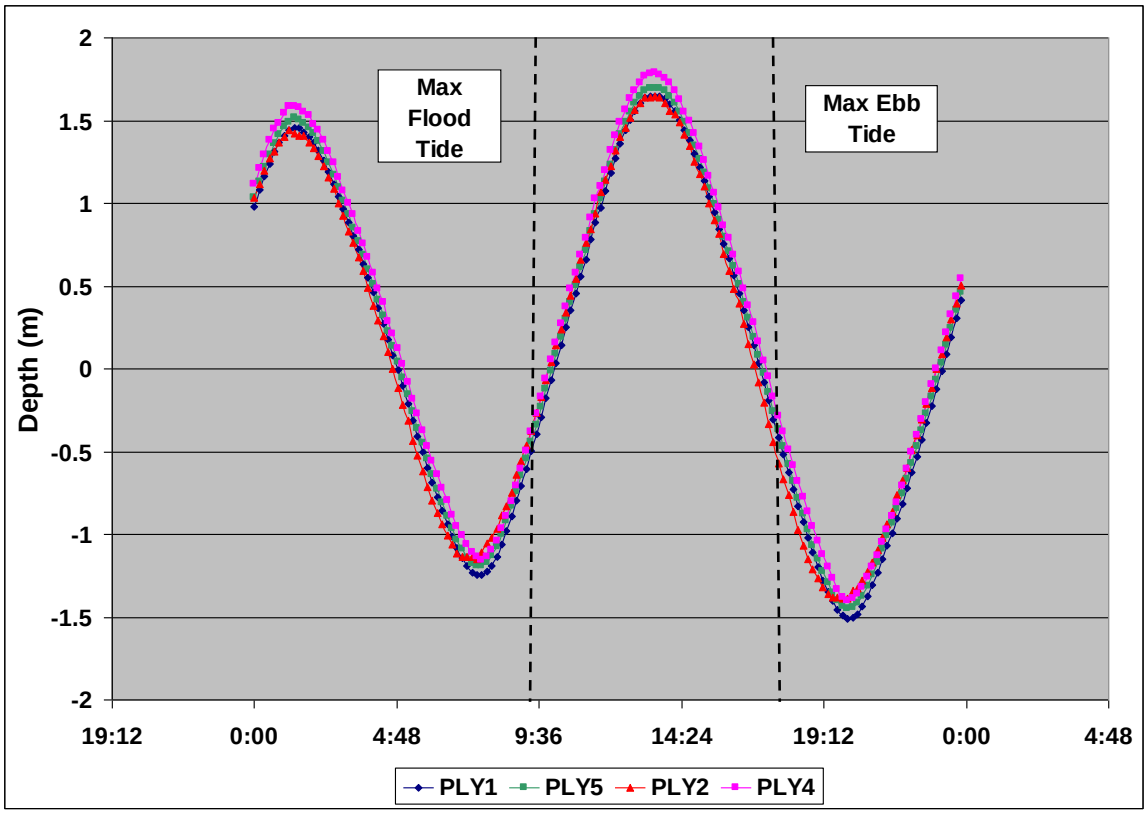

Figure 15. Water surface elevation (tidal stage) on 1st Nov 2012 during the ADCP survey period. Vertical dashed lines indicate the points during the tidal cycle when maximum flood and ebb velocities were measured.

It is also worth noting that based on the ADCP measurements, it appears that the ebb tide current velocities along Transect 1 are more intense than the flood tide current velocities whereas just the opposite is the case for Transect 2. As water fills the southern portion of the overall embayment system, it appears that flood tide current velocities along Transect 2 are more intense than the ebb tide current velocities. This detail will be more accurately evaluated by the future numerical hydrodynamic model developed as part of the MEP analysis.

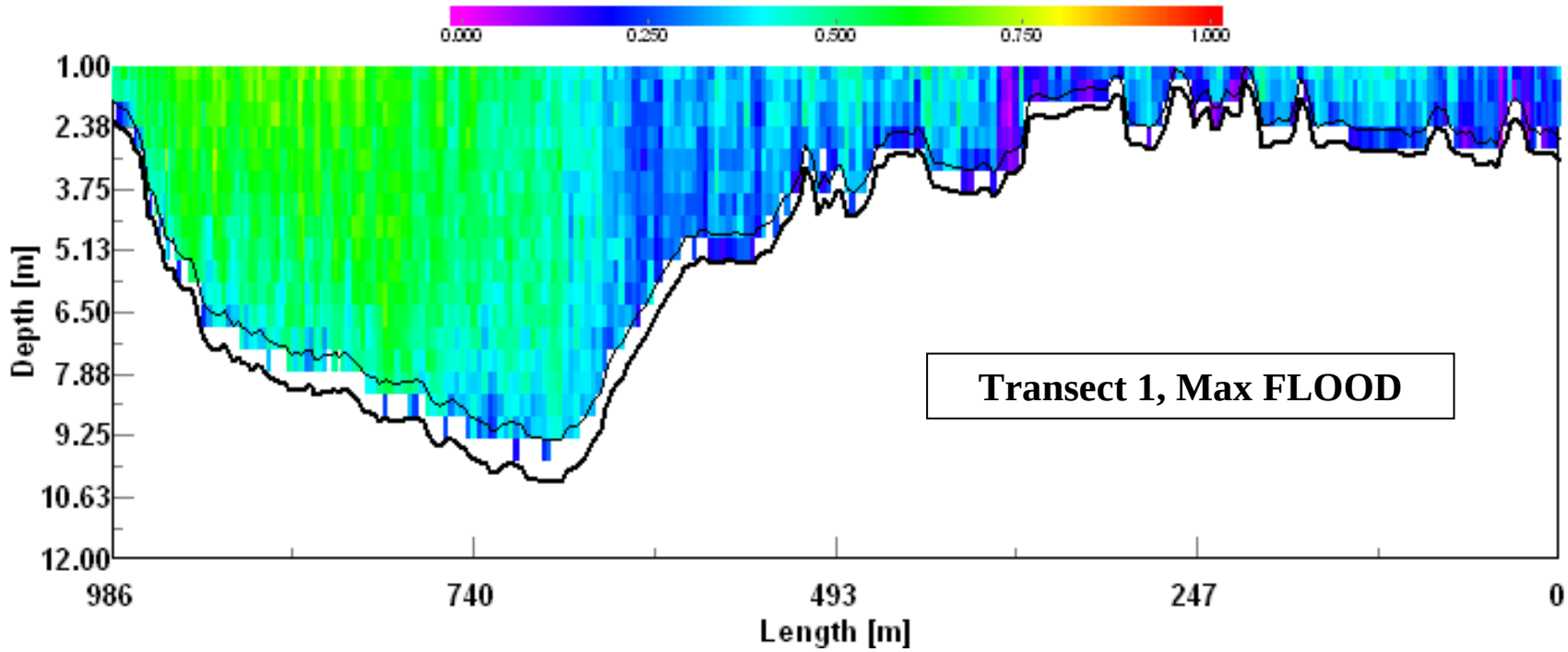

Figure 16. Velocity magnitude plots (m/s) for ADCP Transect 1 (Duxbury Harbor/Cowyard Channel) during the ***max flood*** portion of the tidal cycle. Tide floods north and ebbs to the south.

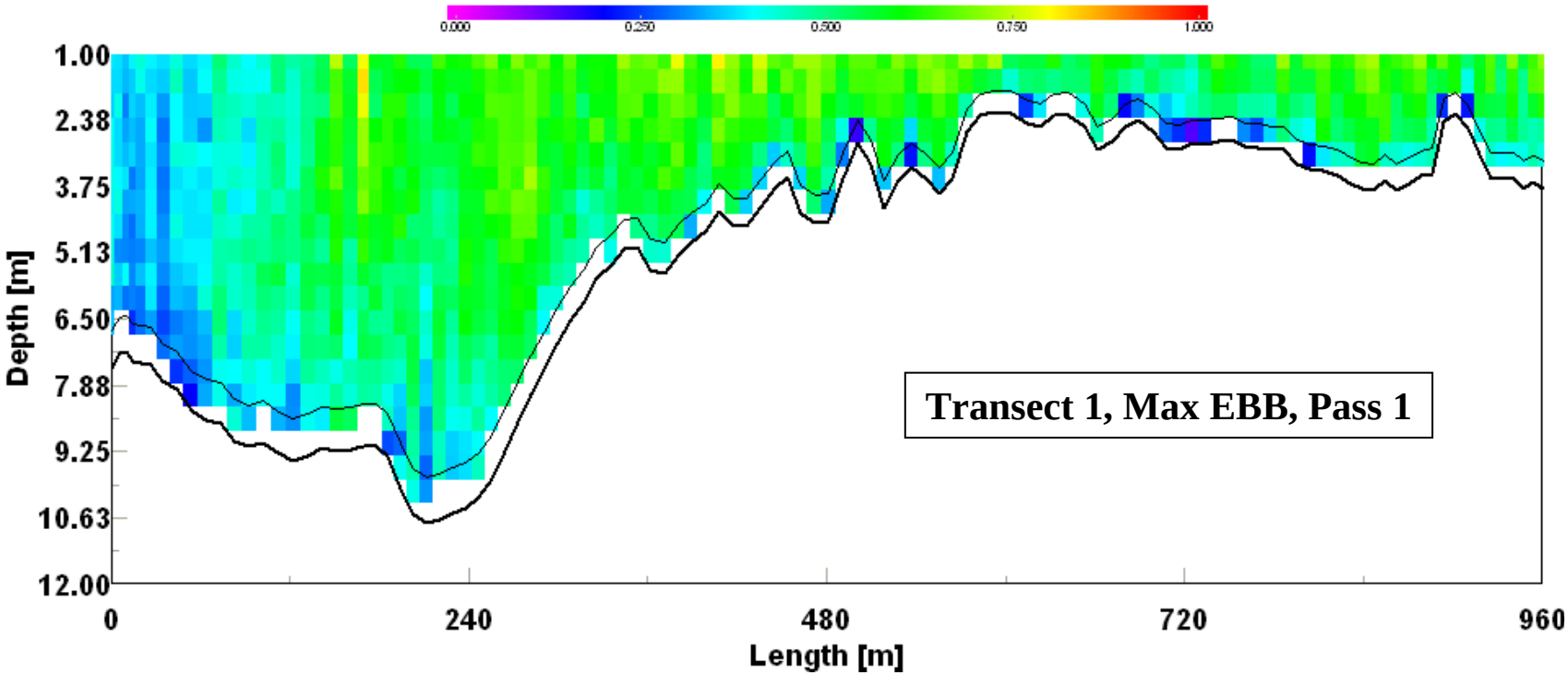

Figure 17. Pass 1 Velocity magnitude plots (m/s) for ADCP survey of Transect 1 (Duxbury Harbor/Cowyard Channel) during the ***max ebb*** portion of the tidal cycle. Tide floods north and ebbs to the south. Transect plots are orientated West to East. Two passes were completed in the hour of maximum ebb tide velocity.

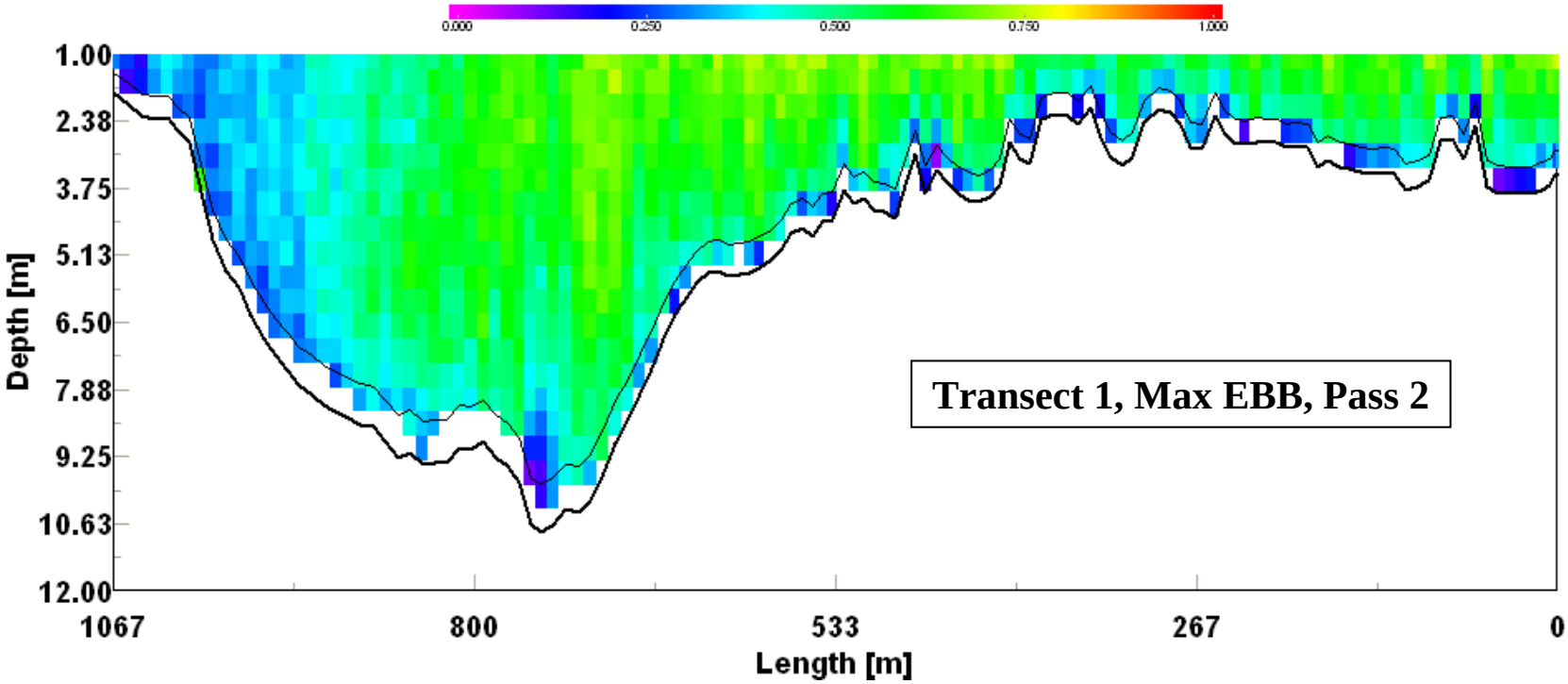

Figure 18. Pass 2 Velocity magnitude plots (m/s) for ADCP survey of Transect 1 (Duxbury Harbor/Cowyard Channel) during the ***max ebb*** portion of the tidal cycle. Tide floods north and ebbs to the south. Transect plots are orientated West to East. Two passes were completed in the hour of maximum ebb tide velocity.

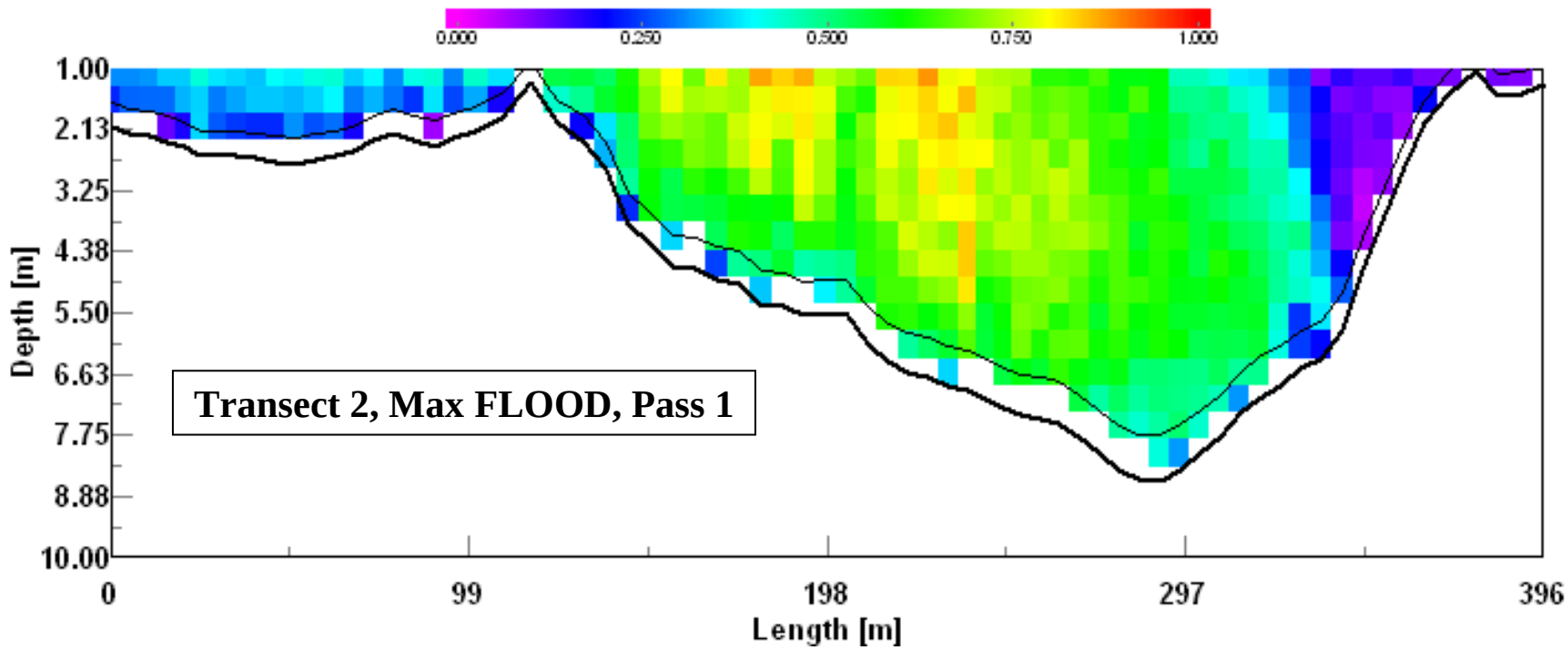

Figure 19. Pass 1 Velocity magnitude plots (m/s) for ADCP survey of Transect 2 (Plymouth Harbor) during the ***max flood*** portion of the tidal cycle. Tide floods south and ebbs to the north. Two passes were completed in the hour of maximum flood tide velocity.

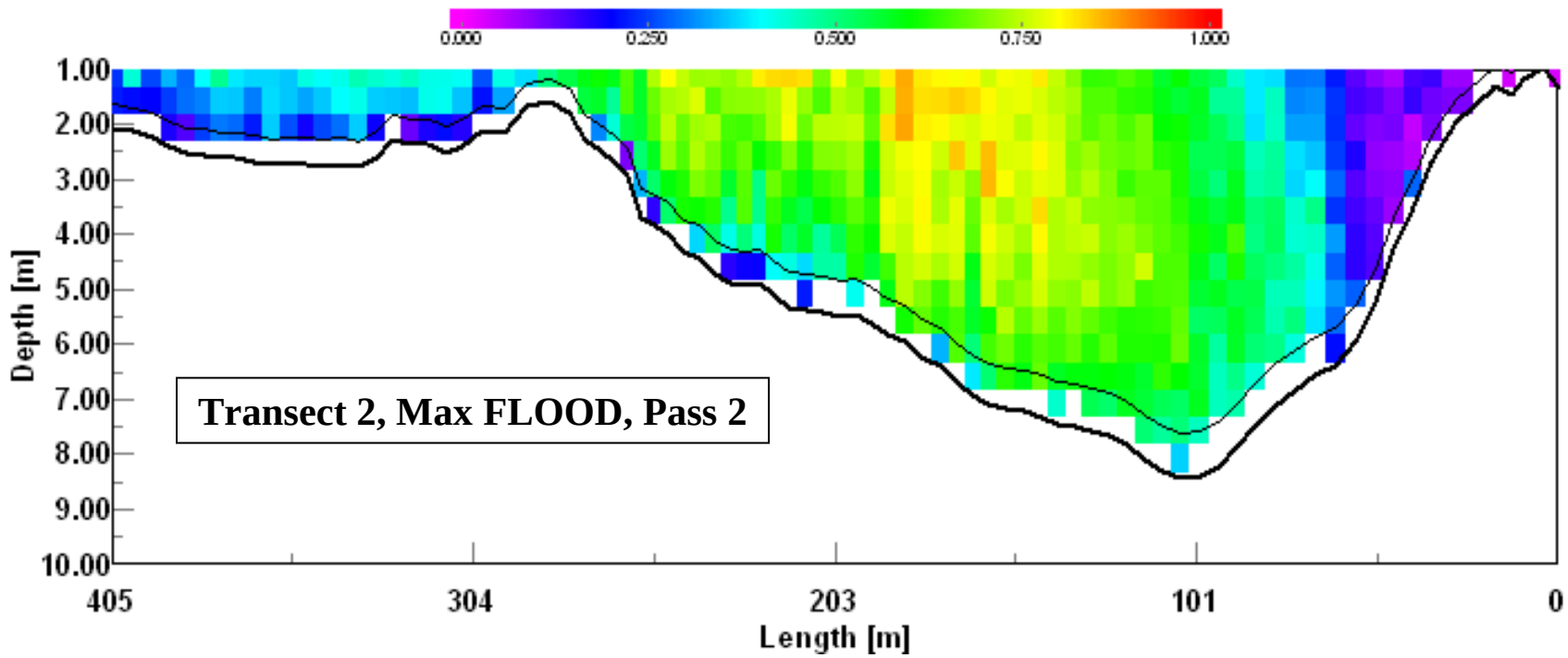

Figure 20. Pass 2 Velocity magnitude plots (m/s) for ADCP survey of Transect 2 (Plymouth Harbor) during the ***max flood*** portion of the tidal cycle. Tide floods south and ebbs to the north. Two passes were completed in the hour of maximum flood tide velocity.

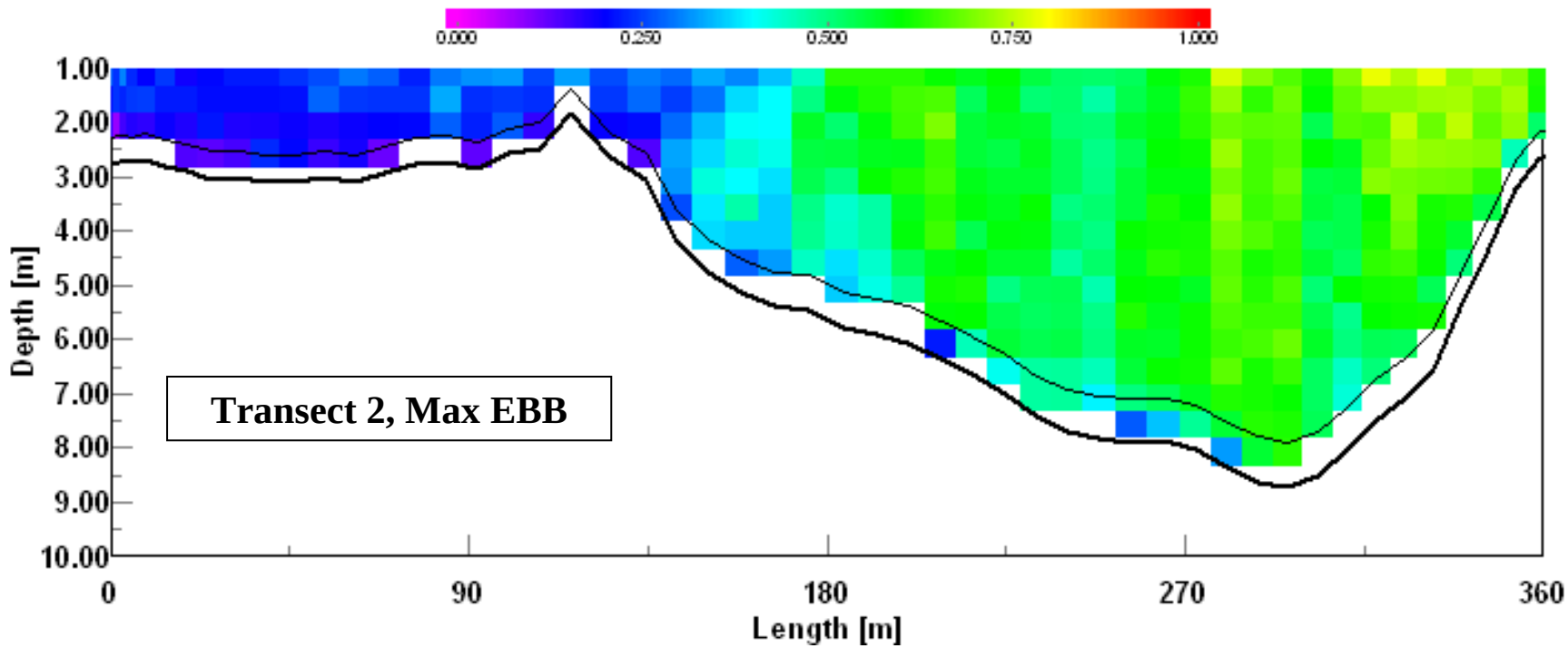

Figure 21. Velocity magnitude (m/s) plot for ADCP survey of Transect 2 (Plymouth Harbor) during the ***max ebb*** portion of the tidal cycle. Tide floods south and ebbs to the north.

ADCP Transect 1 (Cowyard Channel area):
At the northern survey transect (TR1), a maximum depth averaged current velocity was measured to be 0.65 m/sec (1.26 knots) during max flood tide (mid flood) (Figure 22, cycles 1a,1b). Current velocities were observed to be greatest within the main channel (0 - 300 meters) and decrease slightly along the shallower sections of the transect line (Figure 22). Across the entire transect, the mean depth averaged current velocity during max flood was calculated to be 0.37 m/sec (0.72 knots). From the observed measurements, it appears that as the tide changes from flood to ebb, current along the eastern section of the survey line switches direction and begins to ebb prior to the main channel (Figure 22, cycles 3, 4). This observation may be attributed to the shallower water depth along this area (4.0 - 6.0 meters) when compared to the main channel (~ 12.0 meters) and the location relative to the opening to Cape Cod Bay. During max ebb tide (mid ebb), the maximum depth averaged current velocity measured 0.67 m/sec (1.3 knots) along the transect line (Figure 22, cycles 8-9). The mean depth averaged current velocity for the entire transect was calculated at 0.51 m/sec (0.99 knots). For the northern transect tidal exchange appears to be dominated by the ebb tide phase of the tide cycle.

ADCP Transect 2 (Plymouth Harbor main channel entrance):
For the survey of the southern transect (TR2), the flood/ebb tidal regime occurs in the opposite direction when compared to northern site. The system floods to the south but ebbs to the north. Along this transect a maximum depth averaged current velocity of 0.78 m/sec (1.52 knots) was measured during the max flood tide (mid flood) (Figure 23, cycles1a-1b). Across the entire transect, the mean depth averaged current velocity was calculated to be 0.46 m/sec (0.89 knots) at max flood tide. The eastern section of the survey line (100.0 - 400.0 meters) which comprises the main channel, was observed to experience the changing of the tide before the shallower western (0 - 100.0 meters). During max ebb (mid ebb) tide, the maximum depth averaged current velocity measured 0.67 m/sec (1.30 knots) (Figure 23, cycle 10). The mean depth averaged current velocity for the entire transect was calculated at 0.41 m/sec (0.80 knots) during max ebb tide. Tidal exchange along this transect appears to be dominated by the flood tide phase of the tidal cycle.

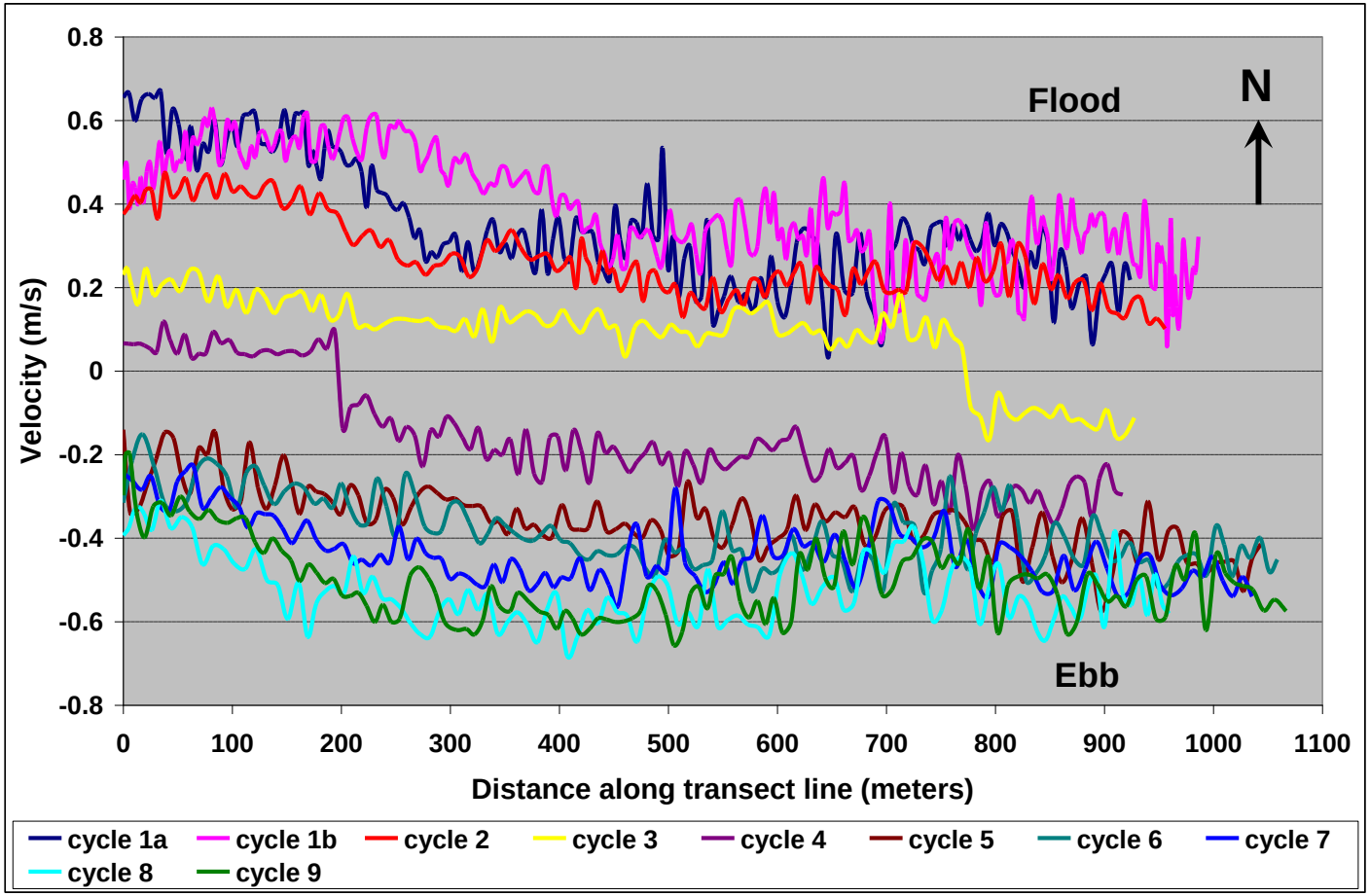

Figure 22. Plot of depth averaged current velocity along survey transect survey transect 1 (TR1). Distance along the transect line is orientated from west to east. Flood tide velocities (circles) and Ebb tide velocities (triangles) are displayed in meters per second. Tide velocity magnitude direction is plotted as north (+) and south (-). The main channel is located between 0 and 300 meters along the survey transect.

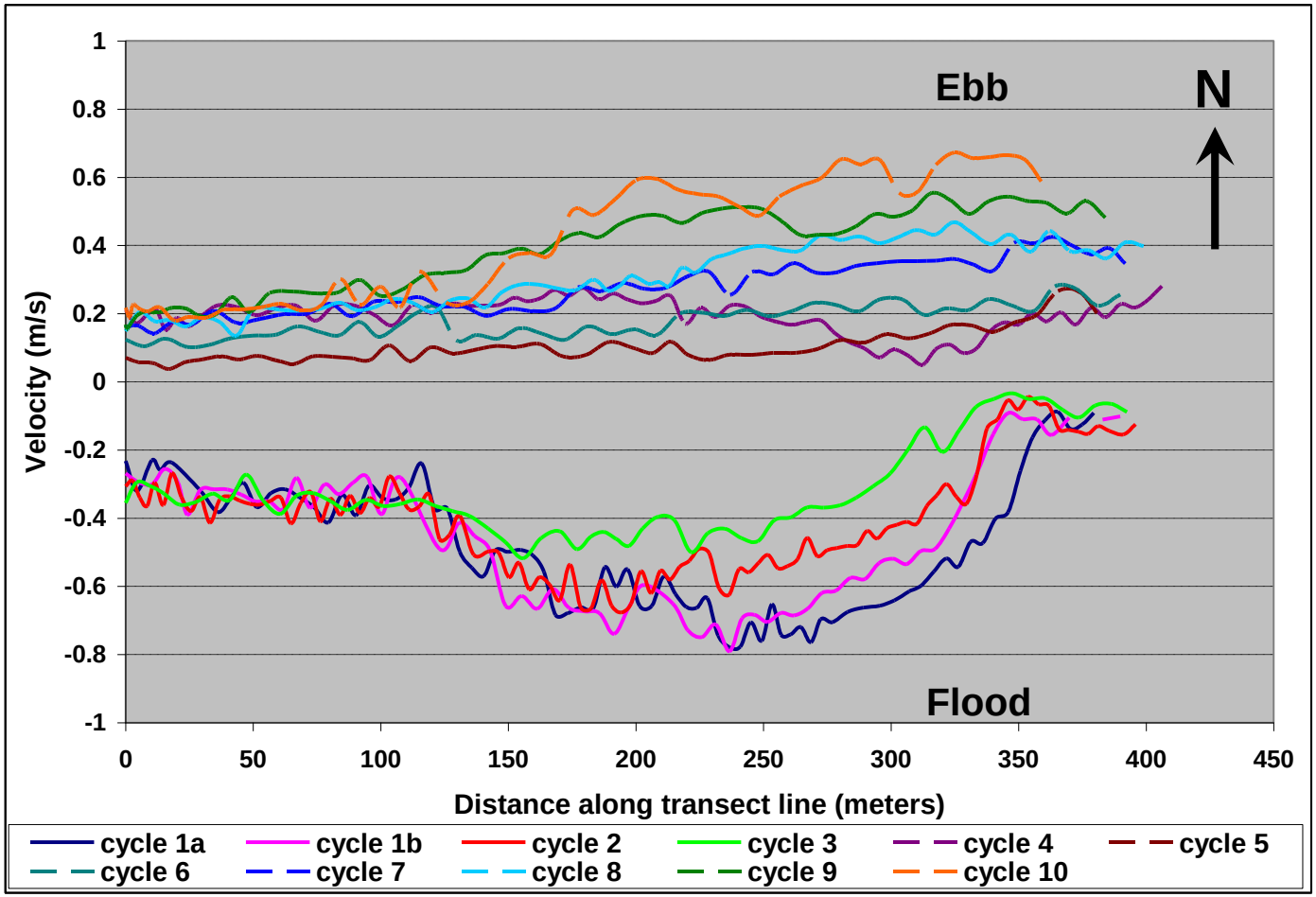

Figure 23. Plot of depth averaged current velocity along survey transect 2 (TR2). Distance along the transect line is orientated from west to east direction. Flood tide velocities (circles) and Ebb tide velocities (triangles) are displayed in meters per second. Tide velocity magnitude direction is plotted as north (+) and south (-). The main harbor channel is located between 100 and 400 meters along the survey transect.

Conclusions:

Although this is meant as a data report from the field bathymetric, tide elevation and ADCP surveys of the Plymouth-Duxbury-Kingston Harbor embayment system, and the quantitative findings required for the development of the hydrodynamic model, there are some key points that should be made here.

- The hydrodynamic data collected to date, is sufficient to support the MEP hydrodynamic modeling effort (both calibration and verification) should funds become available;.
- All of the tidal stage records (4) indicate negligible temporal lag between the recorded high tide at the offshore gage compared to the recorded high tide at each inshore locations;
- Similarly, there was negligible damping of tidal heights;
- The lack of temporal lags or damping of tidal heights support the contention that there is generally unrestricted flow between the offshore gauge and each inshore gauge site.